



The ABB ETG (Electric Tug)

Electric and Hybrid Tug - Analysis
Dave Lee, April 2022

“At ABB, we are pioneering the adoption of electric, digital and connected technologies for greater sustainability. Our goal is to help designers, shipowners, and shipyards with the latest technologies to advance maritime safety, while protecting our planet.”

Dave Lee, Senior Account Manager

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1. Purpose

This document discusses the operational theory of electric and hybrid tugs compared to traditional diesel mechanical designs. The objective is to identify and discuss the operational, maintenance and emission (CO₂) savings between electric and hybrid tugs and a diesel mechanical tug. As a point of clarification this paper will only be specifically discussing a harbour tractor tug and not associated with any discussion on inland push boats (towboats). All savings will be dependent on the specific operator's operation of their tug. In this document we will utilize a single operational profile to simplify the analysis.

NOTE: This paper will not discuss the shore charging solutions or designs; however, this is a very important aspect of any tug design that includes charging of batteries from the shore. The shore charging equipment and configuration should be an integral part of the design for the tug's on-board power distribution system.

2. Foreword

Harbor tugs are an essential component of the global transportation system. Over 90 percent of international trade takes place through shipping carriers and 4 percent of domestic freight goes through the United States river system. Most of the ships carrying the goods in and out of the United States depend on harbor tugs assistance.

Tugs are designed to be highly maneuverable carrying the necessary power to maintain absolute control over any ship that are tethered to. In addition, the low utilization of the tug and the power installed remains one constant operational theme. The power installed in line with United States Coast Guard (USCG) guidelines and depends on the ship's cargo, size and area of operation.

In this whitepaper, we delve deeper into the operational and technical aspects of tugs that are crucial for seamless vessel operation.

ocean going vessels (OGV) at berth, harbor craft (ferries, tugs, and other service vessels), and drayage (trucks used to transport containers and cargo within port boundaries). These account for over 80 percent of criteria pollutants and particulate matter (US EPA 2016).

Throughout this whitepaper we will discuss the emission savings of electric and hybrid tugs compared to a diesel mechanical tug powered by engines following the latest U.S. Environmental Protection Agency (EPA) Tier 4 requirements for marine diesel engines.

A comparative study between electric and hybrid system using a much lower EPA engine tier rating shows higher energy savings which has been explained further in the paper.

However, to keep matters simple, we will be discussing a new build tug in the United States and thus the owner only has the option of selecting a tier 4 diesel mechanical system, an electric system, or a hybrid system for main propulsion.

Finally, this paper will utilize the profile for a 65 MT harbor tug with 4000 kW (5365 HP) of total installed propulsion power with no requirement for firefighting abilities. To remain on the focus of our paper, firefighting (FiFi) requirements in choosing an electric or hybrid system have not been included.

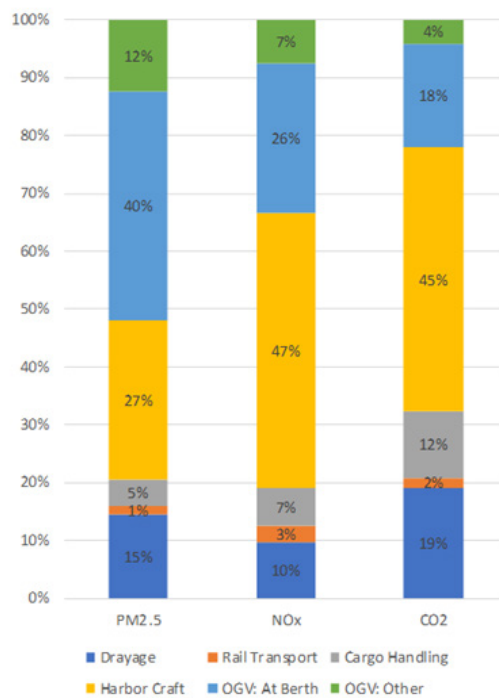


Figure 1

Even though the total yearly hours of operation for a tug are low they are still a major contributor to the overall emissions in the port operations. Figure 1 shows the emissions by various types of port transportations for all major US ports. The three categories of port transportation listed here are

3. Analysis

3.1. Operational Profile

The specific operational profile utilized throughout this comparison study is seen in Figure 2. The key items to take note of are the low operational hours (3400 hrs) and low utilization of the total power installed. The left side of Figure 2 below illustrates that a typical harbor tug utilizes the 50-100% range of horsepower around 2% of its operational life. This is common across many areas of operation in the U.S. tug fleet.

Also, please take note that the tug remains on generator only while at the dock for 2600 hours per year. The other remaining time in the year the tug is considered shutdown completely.

Figure 3 demonstrates the tug’s trip profile for a single trip. Note, the tug completes two identical trips per day and each trip is 280 minutes in duration for a total of 560 operational minutes per day. Figure 3 is a visual depiction of a typical power demand for this route.

Lastly, it is important for an electric system, is the available charge time per trip. The charge time is 360 minutes per trip or a total of 720 minutes per day.

Going ahead, Figure 2 & 3 will be utilized exclusively for both operational and emission analysis.

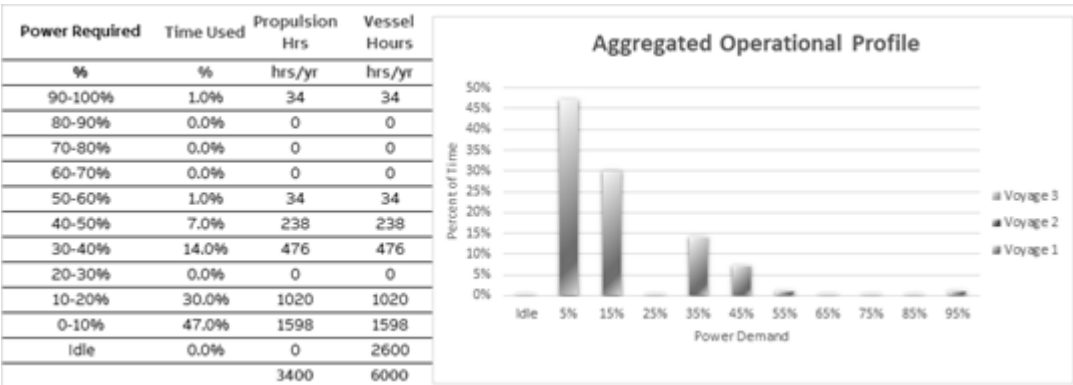


Figure 2

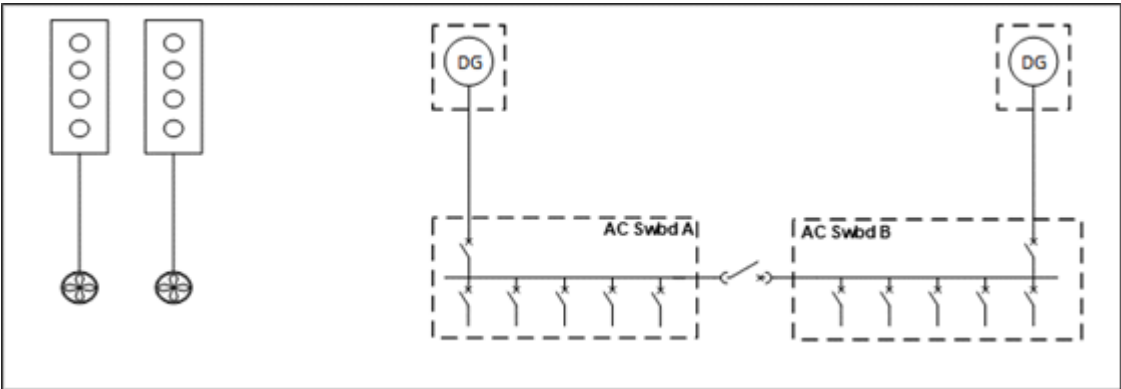


Figure 3

3.2. Diesel Mechanical

Figure 4 demonstrates the diesel mechanical configuration, which historically has been the preferred propulsion system for a tug. In this configuration, the tug typically consists of four diesel internal combustion engines (ICE). Two of the diesel engines are utilized to drive each propeller and the smaller engines are utilized to drive generators that provide power to electrical consumers (shown as AC Swbd A & B) onboard the tug. In this configuration, if the tug is required to provide any amount of operational power, both engines must be running along with one of the generator engines. Meaning of the four engines installed three must always be running during operation.

In the Table 1 & 2 below the foundations for this paper are detailed in terms of operational and emission metrics. The first item to discuss is the engine hours per year. Since both main engines are online and one diesel generator is online during the tug’s operation, the total cumulative engine hours per year are 12,800 hrs. This is required even though the tug only operates 3400 hrs. per year.

Second, the engines utilized for the comparison are EPA Tier 4 the most common engine type currently installed on new build diesel mechanical tugs. Tier 4 engines utilize urea after treatment systems to inject into the exhaust of the engine to treat the exhaust as it exits. For each section, the need for urea aftertreatment will be discussed and compared to the base case listed in Table 1.

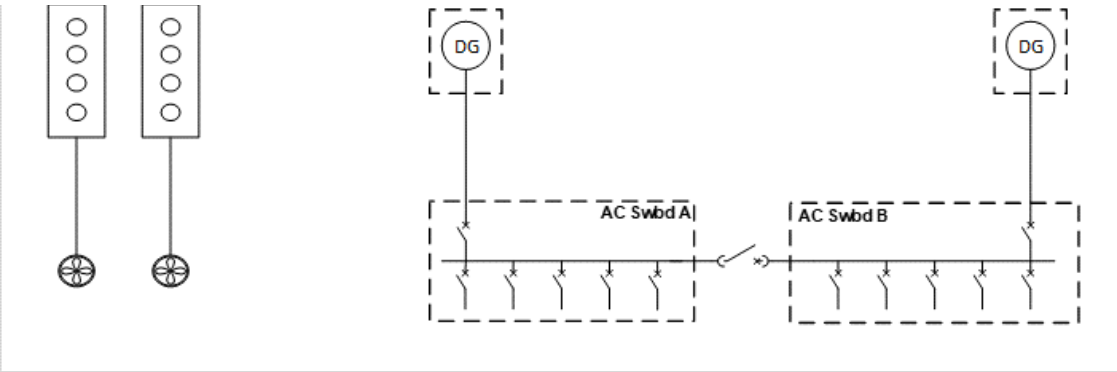


Figure4

FUEL AND RUNNING HOURS		(0) Diesel Mechanical (DM)	
Diesel fuel consumed		167,203	gallons/yr
UREA (DEF) consumed		9,352	gallons/yr
LNG fuel consumed		0	mmBTU/yr
Electricity consumed		0	kWhe/yr
Hydrogen consumed		0	kg/yr
Engine Hours	Propulsion / Primary Genset	6,800	hrs/yr
	Aux / Secondary Gensets	6,000	hrs/yr
	Total	12,800	hrs/yr
Running Hour Savings		--	hr/yr
Fuel/Electricity Savings		--	\$/yr
Urea (DEF) Savings		--	\$/yr
Maintenance Savings		--	\$/yr
TOTAL SAVINGS		--	\$/yr

Table 1
Operational Savings

Table 2
Emission Savings

FUEL AND RUNNING HOURS		(0) Diesel Mechanical (DM)	
Diesel Fuel consumed		167,203	gallons/yr
LNG fuel consumed		0	gallons/yr
Electricity consumed		0	kWhe/yr
Hydrogen (gray) consumed		0	kg/yr
EMISSIONS TOTALS*			
Diesel Fuel CO ₂ emissions		1,702,122	kg CO ₂ /yr
LNG Fuel CO ₂ emissions		0	kg CO ₂ /yr
Electricity CO ₂ emissions		0	kg CO ₂ /yr
Hydrogen CO ₂ emissions		0	kg CO ₂ /yr
TOTAL EMISSIONS		1,702,122	kg CO ₂ /yr
*diesel emissions intensity per EPA; electric emissions intensity based on avh			
TOTAL REDUCTION		--	kg CO ₂ /yr
1 Car = 4600 kg CO ₂ /YR - US EPA		--	cars off the road

3.3. Shaft Generator (PTO/PTI)

The shaft generator configuration as seen in Figure 5, is the first step that tug owners in the US have started to deploy to reduce greenhouse gas emissions. In the PTO/PTI configuration the diesel engine is still utilized as the main source of propulsion power; however, an integral motor or motor/ generator is installed for hybrid mode (note: the current systems installed in the U.S. have only included the integral motor and not a motor/ generator). The PTO/PTI system analyzed included four diesel engines: two for propulsion & two for diesel generators. Therefore, it is a variation of the base case diesel mechanical.

In the power take in (PTI) operation mode the diesel generators can be utilized to provide not only the electrical consumers on board but now they can be utilized to also provide propulsion power. In this configuration, the diesel generators are typically larger than what is currently installed in a tug because it serves a dual purpose. The benefit that the tug operator gains is that the generator power can be utilized for transit operations at low load with the main diesel engines offline. The second benefit that can be realized is the generators can act as boost power for the propulsion system at high demands and in some cases, this may allow the operator to drop the size of the main engines that they would typically install. There are many different variations available for a PTI configuration, but

some limit the flexibility to add the additional PTO mode to the system.

In the power take out (PTO) operation mode the motor/ generator can draw power from the main diesel engine while it is in an operational point that the specific fuel oil consumption is much more favorable than that of the diesel gensets. The power that is generated from the motor/ generator is much less consuming of the diesel fuel on board and thus expensive for the operator. In the PTO mode the electric that is produced can be utilized for the electrical consumers onboard the tug. Also, in many cases, the power produced is much more than what is required for consumers so in Figure 5 the PTO/PTI system analyzed also considers installed batteries to capture the additional power.

Installed batteries allow operators to realize additional benefits as power can be stored and then utilized with the installed electric motors in PTI mode for zero emission operations where there are no diesel engines online or for boost mode without the utilization of the diesel generators.

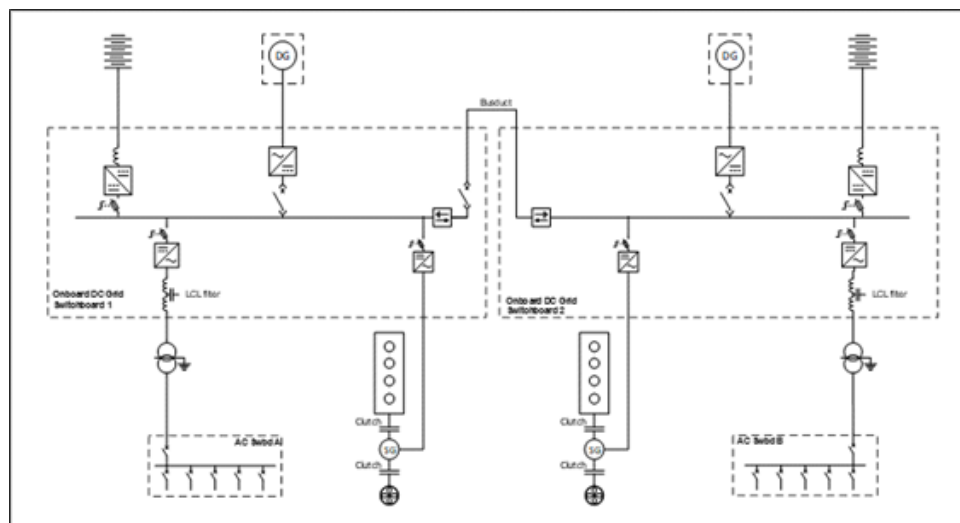


Figure 5

Table 3 shows that as the hybrid systems are introduced into the configuration the operational savings per year are immediately realized. In the table below there are several items to point out:

1. Running Hour savings: Because batteries are installed, and the tug is able to operate in PTO & PTI mode the installed diesel generators are not utilized and the main diesel engines are only online at higher load demands.
2. Fuel/ Urea savings: With the reduction of the main engine running hours the need for the urea treatment is also reduced leading to a reduction in urea and fuel usage.
3. Maintenance savings: Many diesel engine manufacturers have set maintenance intervals on fuel usage or overall engine running hours. With each interval the complexity and cost of the intervention varies; however, throughout this paper the cost was normalized through units of running hours and applied to each configuration depending on hours of engine running hours saved per year.

The table illustrates savings in all the operational categories compared to the base diesel mechanical case. However, much of the savings was due to the fact that batteries were included in the configuration and not due to the selection of a PTO/PTI system per say.

Table 4 demonstrates again as the hybrid system is introduced to the configuration of the tug that emission savings are immediately recognized. In this paper we have converted the total savings of CO₂ into units of cars as many people can relate to emissions of cars versus a marine vessel. Therefore, in the analysis of the PTO/PTI tug there is a savings of CO₂ emissions yearly of 42,689 kg CO₂/ yr. To put into perspective, it is the equivalent of removing 9 automobiles worth of CO₂ emissions per year.

FUEL AND RUNNING HOURS		(0) Diesel Mechanical (DM)	(A) Shaft Generator Vessel	
Diesel fuel consumed		167,203	163,009	gallons/yr
UREA (DEF) consumed		9,352	9,193	gallons/yr
LNG fuel consumed		0	0	mmbTU/yr
Electricity consumed		0	0	kWhe/yr
Hydrogen consumed		0	0	kg/yr
Engine Hours	Propulsion / Primary Genset	6,800	3,084	hrs/yr
	Aux / Secondary Gensets	6,000	2,040	hrs/yr
	Total	12,800	5,124	hrs/yr
Running Hour Savings		--	7,676	hr/yr
Fuel/Electricity Savings		--	\$13,419	\$/yr
Urea (DEF) Savings		--	\$514	\$/yr
Maintenance Savings		--	\$19,592	\$/yr
TOTAL SAVINGS		--	\$33,525	\$/yr

Table 3
Operational Savings

FUEL AND RUNNING HOURS		(0) Diesel Mechanical (DM)	(A) Shaft Generator Vessel	
Diesel Fuel consumed		167,203	163,009	gallons/yr
LNG fuel consumed		0	0	gallons/yr
Electricity consumed		0	0	kWhe/yr
Hydrogen (gray) consumed		0	0	kg/yr
EMISSIONS TOTALS*				
Diesel Fuel CO ₂ emissions		1,702,122	1,659,433	kg CO ₂ /yr
LNG Fuel CO ₂ emissions		0	0	kg CO ₂ /yr
Electricity CO ₂ emissions		0	0	kg CO ₂ /yr
Hydrogen CO ₂ emissions		0	0	kg CO ₂ /yr
TOTAL EMISSIONS		1,702,122	1,659,433	kg CO ₂ /yr
TOTAL REDUCTION		--	42,689	kg CO ₂ /yr
1 Car = 4600 kg CO ₂ /YR - US EPA		--	9	cars off the road

Table 4
Emission Savings

3.4. Diesel Electric

In the diesel mechanical configuration seen in Figure 6 the idea of a traditional diesel mechanical tug configuration has taken a shift. The long-standing idea of the main diesel engine for propulsion and auxiliary diesel generators for consumers NO longer exists. The power for both the vessel propulsion and electrical consumers are provided by common electrical distribution system. In Figure 6 the power is provided by multiple EPA Tier 3 generators. The electrical integration provided is very important to balance the demands of the vessel with the demands of the consumers (winches, hotel load, etc.). The seven generators are needed for the maximum designed power; however, the actual demand will only need three generators running much of the time. The operator enjoys an extreme increase in built-in redundancy and the units are typically provided as skid mount versus fixed mounting and the operator can now start to rethink not only what maintenance is performed on the vessel but also how it is performed.

In Table 5 you can see that in a diesel electric configuration the operational savings are increased; however, it is not a parallel to the PTO/PTI configuration:

1. Running Hour savings: In the diesel electric arrangement running hour savings are realized; however, they are not as great as the PTO/PTI solution. This is due to two factors: one, there are no batteries considered in the diesel electric configuration and two, there are now multiple gensets that are required to produce the power needed.
- a. In other parts of the world, where EPA Tier 4 is not in place, this configuration is changed slightly to increase the power of each diesel genset to reduce the overall number of generators required. This would decrease the number of running hours per year.

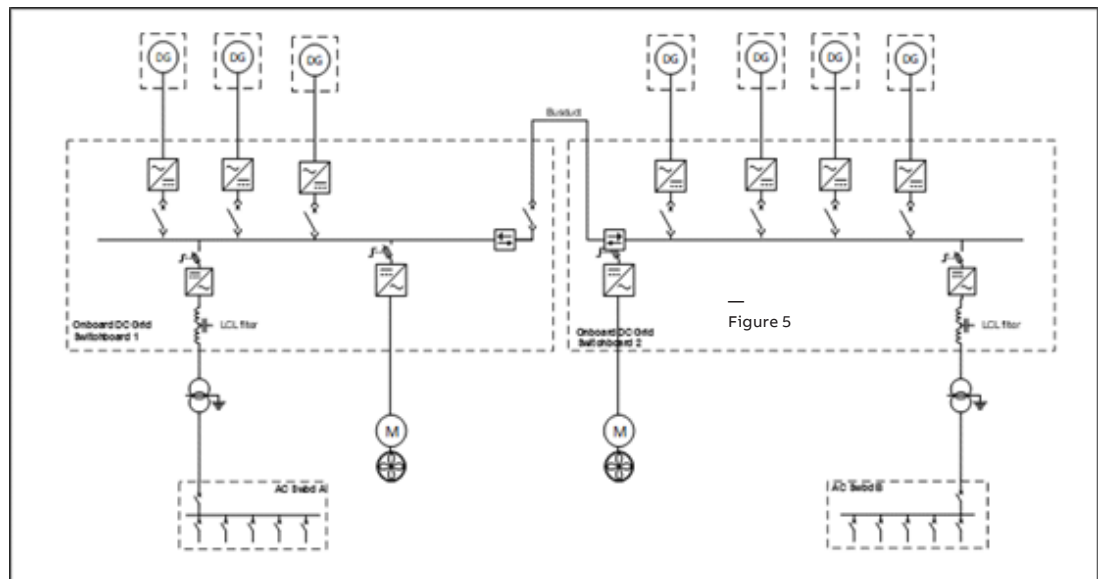


Figure 6

2. Fuel/ Urea savings: In this configuration the diesel engines installed for gensets are all EPA Tier 3 certified and thus there is no need for a urea aftertreatment system. Also, in Table 5 there is a continued fuel savings compared to the base diesel mechanical configuration and the PTO/ PTI configuration.
- a. The majority of the operational time there is a need for only one or two smaller diesel gensets required to meet the power demand, and these gensets are loaded to a favorable point for diesel consumption. This is compared to running the larger main diesel engines at a lower load that is at an unfavorable point for diesel consumption.
3. Maintenance savings: As with the PTO/ PTI configuration before, the running hours per year are reduced with the diesel electric case and maintenance savings are realized compared to diesel mechanical. Again, the regression in savings versus the prior PTO/PTI example is more of an outcome of utilizing batteries in the PTO/PTI configuration versus the systems inherent nature.

You can see in Table 6 that even with a decrease in running hour savings the emission savings have increased. This is due to the strategic utilization of the installed diesel gensets and only using the power required at a given time for a specific operation. This is compared to the PTO/PTI version that requires both main engines to be online for tug operation beyond what the batteries alone could provide. Due to the strategic loading, there is a diesel fuel savings thus the increase in CO₂ emission savings.

In the next section we will see how the introduction of batteries to a diesel electric system affects the comparative analysis.

	(0) Diesel Mechanical (DM)	(A) Shaft Generator Vessel	(B) Diesel Electric (DE)	
FUEL AND RUNNING HOURS				
Diesel fuel consumed	167,203	163,009	144,907	gallons/yr
UREA (DEF) consumed	9,352	9,193	0	gallons/yr
LNG fuel consumed	0	0	0	mmBTU/yr
Electricity consumed	0	0	0	kWhe/yr
Hydrogen consumed	0	0	0	kg/yr
Engine Hours	Propulsion / Primary Genset	6,800	3,084	6,120 hrs/yr
	Aux / Secondary Gensets	6,000	2,040	2,600 hrs/yr
	Total	12,800	5,124	8,720 hrs/yr
Running Hour Savings	--	7,676	4,080	hr/yr
Fuel/Electricity Savings	--	\$13,419	\$71,347	\$/yr
Urea (DEF) Savings	--	\$514	\$30,246	\$/yr
Maintenance Savings	--	\$19,592	\$7,486	\$/yr
TOTAL SAVINGS	--	\$33,525	\$109,078	\$/yr

Table 5
Operational Savings

Table 6
Emission Savings

	(0) Diesel Mechanical (DM)	(A) Shaft Generator Vessel	(B) Diesel Electric (DE)	
FUEL AND RUNNING HOURS				
Diesel Fuel consumed	167,203	163,009	144,907	gallons/yr
LNG fuel consumed	0	0	0	gallons/yr
Electricity consumed	0	0	0	kWhe/yr
Hydrogen (gas) consumed	0	0	0	kg/yr
EMISSIONS TOTALS*				
Diesel Fuel CO ₂ emissions	1,702,122	1,659,433	1,475,150	kg CO ₂ /yr
LNG Fuel CO ₂ emissions	0	0	0	kg CO ₂ /yr
Electricity CO ₂ emissions	0	0	0	kg CO ₂ /yr
Hydrogen CO ₂ emissions	0	0	0	kg CO ₂ /yr
TOTAL EMISSIONS	1,702,122	1,659,433	1,475,150	kg CO₂/yr
<small>*diesel emissions intensity per EPA; electric emissions intensity based on average for US</small>				
TOTAL REDUCTION	--	42,689	226,972	kg CO₂/yr
<small>1 Car = 4800 kg CO₂/yr - US EPA</small>	--	9	49	cars off the road

3.5. Diesel Electric including battery for peak shave

In the diesel electric configuration with batteries installed for peak shaving there is no difference in the distribution system or the configuration, compared to the diesel electric configuration, except for the addition of batteries. In Figure 7 the power is still provided by multiple Tier 3 generators; however, the total number required has dropped from 7 to 6 compared to the diesel electric case due to the installation of the batteries. The batteries will take the peak demands the vessel will see for the short periods of time in the operational profile compared to reliance on diesel generators that are installed and would rarely be utilized in the diesel electric case.

Simply put, in this configuration the diesel generators will recharge the installed batteries when depleted and while the vessel is still completing the trip in the profile section. However, the recharge time will be dependent on how much power from the diesel gensets is required for operation.

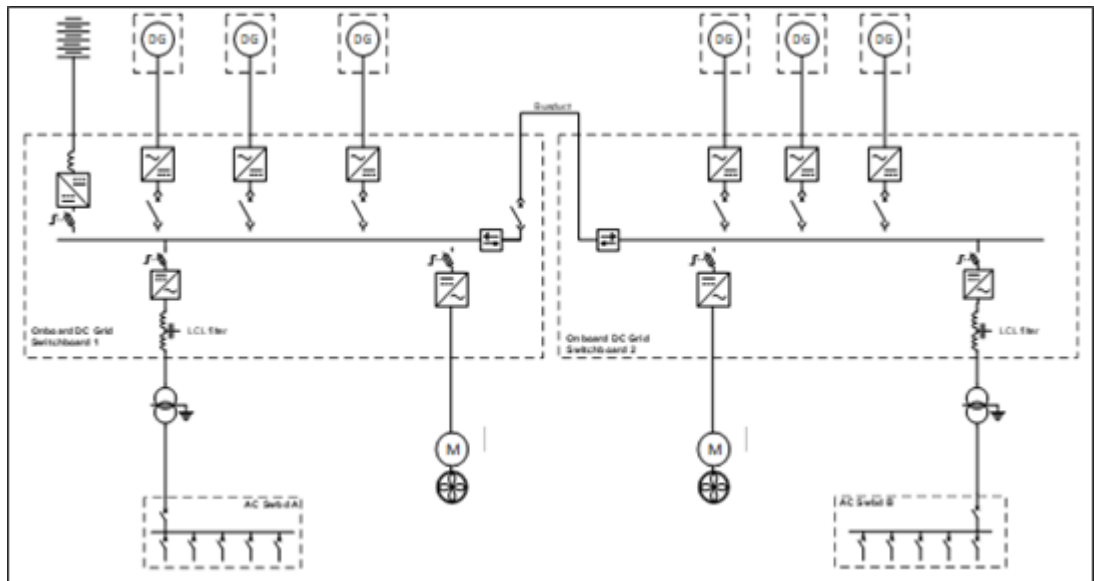


Figure 7

Table 7 shows that in a diesel electric with battery for peak shave configuration the operational savings are increased once again compared to the prior configurations.

1. Running Hour savings: In the diesel electric with battery for peak shave the diesel engine running hour savings have increased compared to the diesel electric option due to strategic loading and peak shaving capabilities the battery enables.
2. Fuel/ Urea savings: Once again, in Table 7 there is a continued fuel savings compared to the prior configuration. In this configuration the continued inherent abilities of a diesel mechanical system allow for strategic loading, but the batteries also now enable the system to not need gensets online.

The other item to point out regarding fuel savings in this configuration is that the batteries are still recharged utilizing the onboard diesel generators. Therefore, the power for the tug is still provided completely by diesel engines.

3. Maintenance savings: The maintenance savings, once again, is calculated on the total running hours per year thus the continued savings compared to the prior configurations.

Table 8 demonstrates an increase in CO₂ emission savings compared to the prior configurations. This is due to the inherent nature of the diesel electric system that enables strategic loading of the gensets. With the introduction of batteries, the diesel fuel savings increases even more and thus the continued increase in CO₂ emission savings.

	(0) Diesel Mechanical (DM)	(A) Shaft Generator Vessel	(B) Diesel Electric (DE)	(C) DE w/Battery for Peak Shave	
FUEL AND RUNNING HOURS					
Diesel fuel consumed	167,203	163,009	144,907	135,264	gallons/yr
UREA (DEF) consumed	9,352	9,193	0	0	gallons/yr
LNG fuel consumed	0	0	0	0	mmBTU/yr
Electricity consumed	0	0	0	0	kWhe/yr
Hydrogen consumed	0	0	0	0	kg/yr
Engine Hours	Propulsion / Primary Genset	6,800	3,084	6,120	3,740 hrs/yr
	Aux / Secondary Gensets	6,000	2,040	2,600	0 hrs/yr
	Total	12,800	5,124	8,720	3,740 hrs/yr
Running Hour Savings	--	7,676	4,080	9,060	hr/yr
Fuel/Electricity Savings	--	\$13,419	\$71,347	\$102,204	\$/yr
Urea (DEF) Savings	--	\$514	\$30,246	\$30,246	\$/yr
Maintenance Savings	--	\$19,592	\$7,486	\$48,740	\$/yr
TOTAL SAVINGS	--	\$33,525	\$109,078	\$181,189	\$/yr

Table 7
Operational Savings

	(0) Diesel Mechanical (DM)	(A) Shaft Generator Vessel	(B) Diesel Electric (DE)	(C) DE w/Battery for Peak Shave	
FUEL AND RUNNING HOURS					
Diesel Fuel consumed	167,203	163,009	144,907	135,267	gallons/yr
LNG fuel consumed	0	0	0	0	gallons/yr
Electricity consumed	0	0	0	0	kWhe/yr
Hydrogen (gray) consumed	0	0	0	0	kg/yr
EMISSIONS TOTALS*					
Diesel Fuel CO ₂ emissions	1,702,122	1,659,433	1,475,150	1,377,019	kg CO ₂ /yr
LNG Fuel CO ₂ emissions	0	0	0	0	kg CO ₂ /yr
Electricity CO ₂ emissions	0	0	0	0	kg CO ₂ /yr
Hydrogen CO ₂ emissions	0	0	0	0	kg CO ₂ /yr
TOTAL EMISSIONS	1,702,122	1,659,433	1,475,150	1,377,019	kg CO ₂ /yr
<i>*diesel emissions intensity per EPA; electric emissions intensity based on average for US</i>					
TOTAL REDUCTION	--	42,689	226,972	325,104	kg CO ₂ /yr
1 Car = 4600 kg CO ₂ /YR - US EPA	--	9	49	70	cars off the road

Table 8
Emission Savings

3.6. Diesel Electric including Battery & Shore Charge

In the diesel electric configuration with batteries installed and shore charging the configuration evolves a bit more compared to the prior configurations. In Figure 8 the power is still provided by batteries and only five diesel gensets. The total number dropped from 6, in the diesel electric with battery for peak shave, to 5 in this configuration by increasing the size of the installed batteries to allow for more of the trip under electric only operation. This is also possible since the shore charging can quickly recharge the batteries in between trips compared to only having the diesel gensets to recharge the batteries in prior configurations.

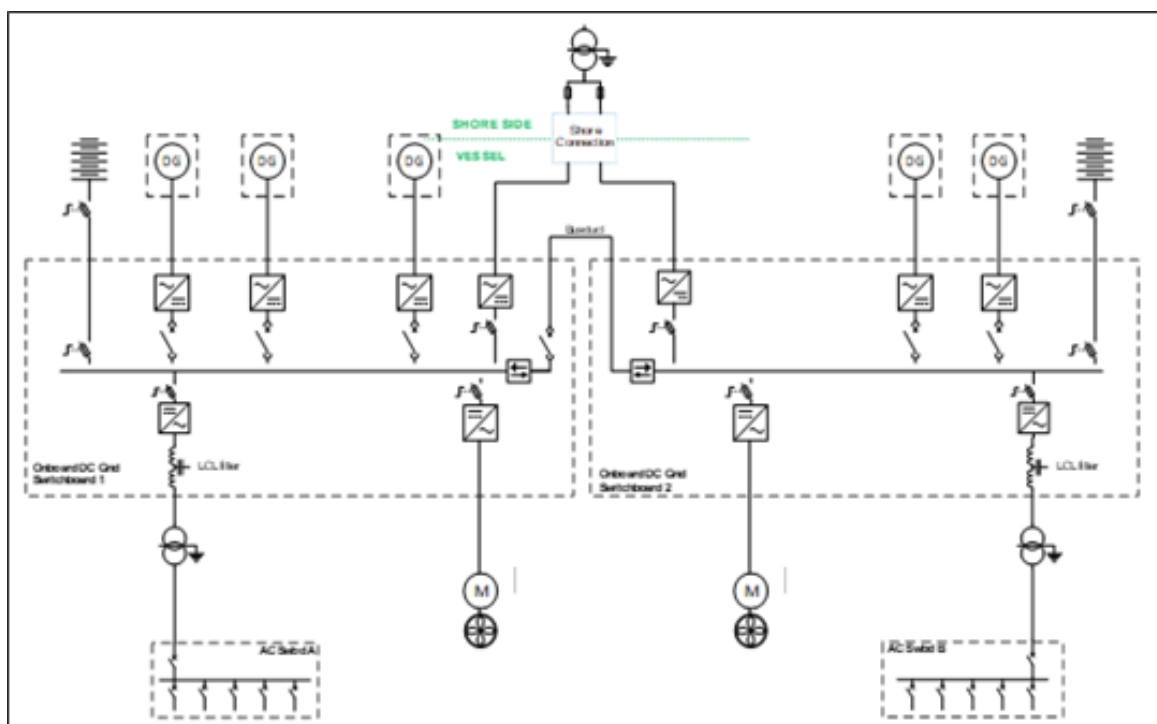


Figure 7

Table 9 shows that in a diesel electric with battery and shore charging the operational savings are increased again compared to the prior configurations.

1. Running Hour savings: In the diesel electric with battery and shore charging the savings follow the trend from before.
2. Fuel/ Urea savings: Regarding fuel, Table 9 demonstrates a shift from diesel consumed to electricity consumed. With the addition of shore charging the need for diesel fuel is diminished. There is still a requirement for diesels due to the power demands at brief peaks and the batteries are not sized for the entire profile; however, the time the diesel generator power is needed is very small. The fuel/ electric savings in Table 9 considers the cost of electricity in a specific region (this cost changes from region to region) plus the 64,566 gallons/yr of diesel still

required so all required energy is accounted for in the comparison, highlighting how much less expensive power from the electrical grid is compared to generating power onboard the tug with diesel generators.

3. Maintenance savings: The maintenance savings, once again, follow the same trend from the sections before.

Table 10 again demonstrates an increase in CO₂ emission savings compared to the prior configurations. The major difference in this configuration is the addition of shore charging and it is in Table 10 that you can see the dramatic difference grid power makes. The CO₂ savings total is not a fixed number and is dependent on the region of operation. As the grid power in one region is produced by mainly nuclear or solar the number can increase; however, as a region produces power typically through coal or natural gas the number will decline.

		(0) Diesel Mechanical (DM)	(A) Shaft Generator Vessel	(B) Diesel Electric (DE)	(C) DE w/Battery for Peak Share	(D) DE w/Battery & Shore Charge	
FUEL AND RUNNING HOURS							
Diesel fuel consumed		167,203	163,009	144,907	135,264	64,566	gallons/yr
UREA (DEF) consumed		9,352	9,193	0	0	0	gallons/yr
LNG fuel consumed		0	0	0	0	0	mmBTU/yr
Electricity consumed		0	0	0	0	1,071,388	kWhe/yr
Hydrogen consumed		0	0	0	0	0	kg/yr
Engine Hours	Propulsion / Primary Genset	6,800	3,084	6,120	3,740	1,777	hrs/yr
	Aux / Secondary Gensets	6,000	2,040	2,600	0	0	hrs/yr
	Total	12,800	5,124	8,720	3,740	1,777	hrs/yr
Running Hour Savings		--	7,676	4,080	9,060	11,023	hr/yr
Fuel/Electricity Savings		--	\$13,419	\$71,347	\$102,204	\$250,761	\$/yr
Urea (DEF) Savings		--	\$514	\$30,246	\$30,246	\$30,246	\$/yr
Maintenance Savings		--	\$19,592	\$7,486	\$48,740	\$54,210	\$/yr
TOTAL SAVINGS		--	\$33,525	\$109,078	\$181,189	\$335,217	\$/yr

Table 9
Operational Savings

		(0) Diesel Mechanical (DM)	(A) Shaft Generator Vessel	(B) Diesel Electric (DE)	(C) DE w/Battery for Peak Share	(D) DE w/Battery & Shore Charge	
FUEL AND RUNNING HOURS							
Diesel Fuel consumed		167,203	163,009	144,907	135,264	64,566	gallons/yr
LNG fuel consumed		0	0	0	0	0	gallons/yr
Electricity consumed		0	0	0	0	1,071,388	kWhe/yr
Hydrogen (gray) consumed		0	0	0	0	0	kg/yr
EMISSIONS TOTALS*							
Diesel Fuel CO ₂ emissions		1,702,122	1,659,433	1,475,150	1,376,987	657,285	kg CO ₂ /yr
LNG Fuel CO ₂ emissions		0	0	0	0	0	kg CO ₂ /yr
Electricity CO ₂ emissions		0	0	0	0	491,242	kg CO ₂ /yr
Hydrogen CO ₂ emissions		0	0	0	0	0	kg CO ₂ /yr
TOTAL EMISSIONS		1,702,122	1,659,433	1,475,150	1,376,987	1,148,526	kg CO₂/yr
*diesel emissions intensity per EPA; electric emissions intensity based on average for US							
TOTAL REDUCTION		--	42,689	226,972	325,136	553,596	kg CO₂/yr
1 Car = 4600 kg CO ₂ /YR - US EPA		--	9	49	70	120	cars off the road

Table 10
Emission Savings

3.7. Battery Electric

In the battery electric configuration seen in Figure 9 the dependence on diesel generated power is almost eliminated. The configuration for the electrical systems is similar to the systems previous however the power for the system is planned to be completely supplied by the batteries with the diesel generator installed as a backup or emergency use only. Therefore, the batteries are to be recharged through only the shore charging network.

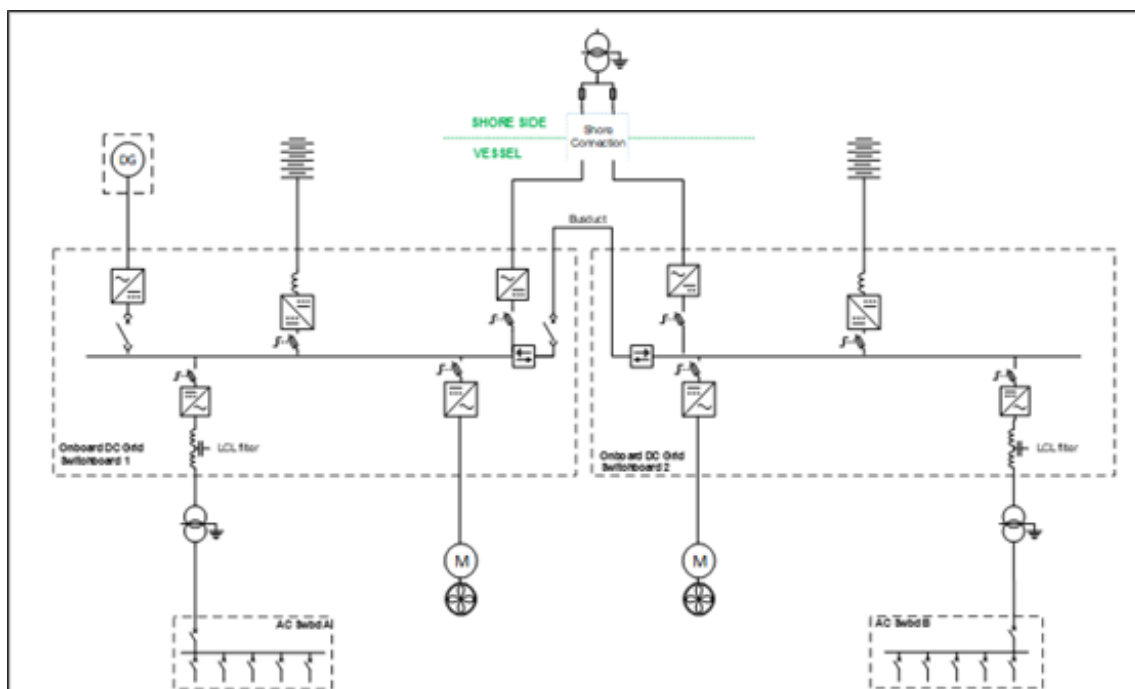


Figure 9

In Table 11 the battery electric numbers make quite a jump compared to the previous configurations.

1. Running Hour savings: In the battery electric configuration the diesel genset is for emergency purposes only; therefore, no diesel genset hours are included in this analysis.
2. Fuel/ Urea savings: The fuel analysis is the most dramatic change in Table 11. The difference between utilizing all power from the grid (shore charging) and nothing from diesel generators is quite dramatic.
3. Maintenance savings: The maintenance savings, in Table 11 is reflective of eliminating of all the diesel engine required maintenance and is accounting for only the maintenance needed for the electrical system and batteries.

In Table 12 please note the effects of relying only on grid power compared to power generated through diesel engines. In the battery electric configuration another major gain in CO₂ emission reducing is realized even though the case prior (DE including battery & shore charging) didn't have much fuel usage. This shows the true impact of completely removing the diesel engines from the solution.

		(0) Diesel Mechanical (DM)	(A) Shaft Generator Vessel	(B) Diesel Electric (DE)	(C) DE w/Battery for Peak Share	(D) DE w/Battery & Shore Charge	(E) Battery Electric Vessel	
FUEL AND RUNNING HOURS								
Diesel fuel consumed		167,203	163,009	144,907	135,264	64,566	0	gallons/yr
UREA (DEF) consumed		9,352	9,193	0	0	0	0	gallons/yr
LNG fuel consumed		0	0	0	0	0	0	mmBTU/yr
Electricity consumed		0	0	0	0	1,071,388	2,179,509	kWhe/yr
Hydrogen consumed		0	0	0	0	0	0	kg/yr
Engine Hours	Propulsion / Primary Genset	6,800	3,084	6,120	3,740	1,777	0	hrs/yr
	Aux / Secondary Gensets	6,000	2,040	2,600	0	0	0	hrs/yr
	Total	12,800	5,124	8,720	3,740	1,777	0	hrs/yr
Running Hour Savings		--	7,676	4,080	9,060	11,023	12,800	hr/yr
Fuel/Electricity Savings		--	\$13,419	\$71,347	\$102,204	\$250,761	\$377,034	\$/yr
Urea (DEF) Savings		--	\$514	\$30,246	\$30,246	\$30,246	\$30,246	\$/yr
Maintenance Savings		--	\$19,592	\$7,486	\$48,740	\$54,210	\$63,634	\$/yr
TOTAL SAVINGS		--	\$33,525	\$109,078	\$181,189	\$335,217	\$470,914	\$/yr

Table 11
Operational Savings

		(0) Diesel Mechanical (DM)	(A) Shaft Generator Vessel	(B) Diesel Electric (DE)	(C) DE w/Battery for Peak Share	(D) DE w/Battery & Shore Charge	(E) Battery Electric Vessel	
FUEL AND RUNNING HOURS								
Diesel fuel consumed		167,203	163,009	144,907	135,264	64,566	0	gallons/yr
LNG fuel consumed		0	0	0	0	0	0	gallons/yr
Electricity consumed		0	0	0	0	1,071,388	2,179,509	kWhe/yr
Hydrogen (gray) consumed		0	0	0	0	0	0	kg/yr
EMISSIONS TOTALS*								
Diesel Fuel CO ₂ emissions		1,702,122	1,659,433	1,475,150	1,376,987	657,285	0	kg CO ₂ /yr
LNG Fuel CO ₂ emissions		0	0	0	0	0	0	kg CO ₂ /yr
Electricity CO ₂ emissions		0	0	0	0	491,242	999,326	kg CO ₂ /yr
Hydrogen CO ₂ emissions		0	0	0	0	0	0	kg CO ₂ /yr
TOTAL EMISSIONS		1,702,122	1,659,433	1,475,150	1,376,987	1,148,526	999,326	kg CO₂/yr
<small>*diesel emissions intensity per EPA; electric emissions intensity based on average for US</small>								
TOTAL REDUCTION		--	42,689	226,972	325,136	553,596	702,797	kg CO₂/yr
<small>1 Car = 4600 kg CO₂/YR - US EPA</small>		--	9	49	70	120	152	cars off the road

Table 12
Emission Savings

3.8. Fuel Cell Electric

In the recent evolution of power, for electric and hybrid tugs, hydrogen fuel cell technology is becoming more than a conversation piece. Figure 10 showcases the utilization of seven 200 kW fuel cell modules for most of the power required and battery for the peak loads. The fuel cell is much like the diesel gensets in prior configurations. As power demands rise or fall, a module is either brought online or shutdown to match what is required. However, fuel cells are not very dynamic in their operation; therefore, batteries are required for not only the peak loads in the configuration but also to cover the dynamic loads that are seen during the tug's operation.

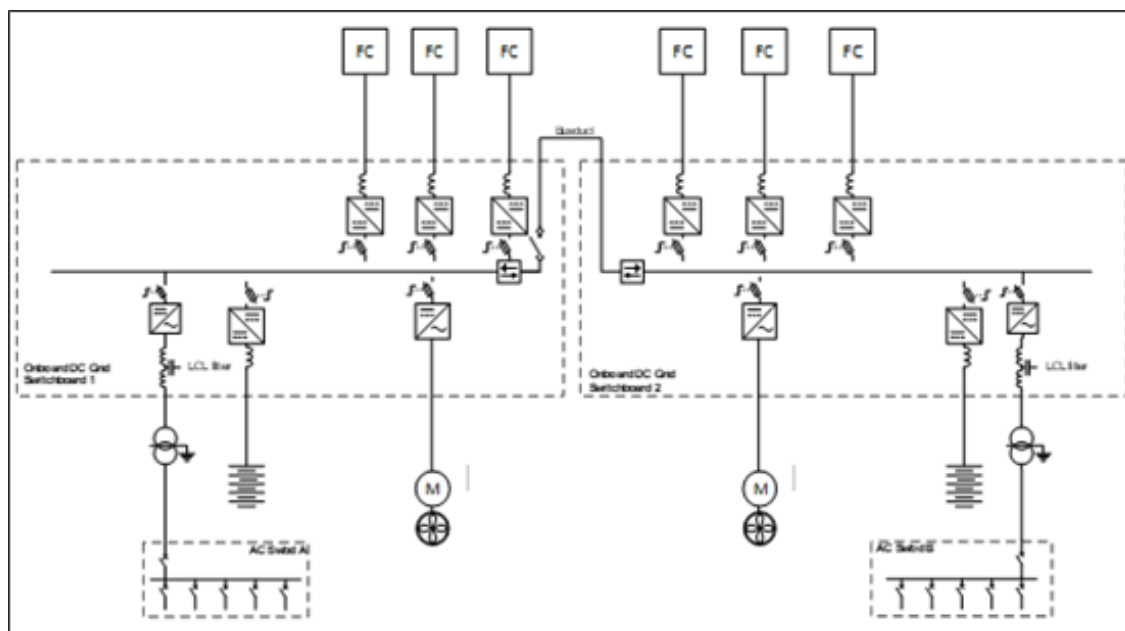


Figure 10

In Table 13 the fuel cell tug makes a shift compared to the other configurations discussed thus far. All the energy used on the tug is now generated solely by the hydrogen fuel cell modules that utilize gray hydrogen as the fuel source.

1. Running Hour savings: As in the battery electric tug configuration there are no requirements for diesel generated power so, there are no engine running hours associated with fuel cell configuration.
2. Fuel/ Urea savings: The fuel savings is now based on the cost of hydrogen needed for the tug versus that of diesel or electricity in previous configurations. Figures for a kg of gray hydrogen is still rough so the numbers used in the analysis is an average of what is commercially available today in the U.S.
3. Maintenance savings: The maintenance savings, in Table 13 is again reflective of eliminating of all the diesel engine required maintenance and is accounting for only the maintenance needed for the electrical system and fuel cell modules.

Table 14 clearly shows the decrease in emission savings in the fuel cell configuration compared to the two prior configurations. This is primarily because grey hydrogen is being utilized as the fuel for the tug.

Currently, green hydrogen is a scarce resource in the United States thus the use of grey hydrogen in the analysis. Grey hydrogen is produced from fossil fuels such as natural gas and thus is very carbon intensive. Grey carbon is not seen as the way forward as hydrogen fuel cells become more popular. Green hydrogen is the ultimate goal around the world, which is produced through energy that is generated by wind or solar. So, as we see the transition from grey to green hydrogen, the CO₂ savings could eliminate the entire 1,702,122 kg of CO₂/yr (370 cars) the current diesel mechanical tugs emit.

FUEL AND RUNNING HOURS	Mechanical (DM)	Generator Vessel	Electric (DE)	for Peak Share	& Shore Charge	Electric Vessel	(Gray H2)	
Diesel fuel consumed	167,203	163,009	144,907	135,264	64,566	0	0	gallons/yr
UREA (DEF) consumed	9,352	9,193	0	0	0	0	0	gallons/yr
LNG fuel consumed	0	0	0	0	0	0	0	mmBTU/yr
Electricity consumed	0	0	0	0	1,071,388	2,179,509	0	kWhe/yr
Hydrogen consumed	0	0	0	0	0	0	141,372	kg/yr
Engine Hours	Propulsion / Primary Genset	6,800	3,084	6,120	3,740	1,777	0	hrs/yr
	Aux / Secondary Gensets	6,000	2,040	2,600	0	0	0	hrs/yr
	Total	12,800	5,124	8,720	3,740	1,777	0	hrs/yr
Running Hour Savings	--	7,676	4,080	9,060	11,023	12,800	12,800	hr/yr
Fuel/Electricity Savings	--	\$13,419	\$71,347	\$102,204	\$250,761	\$377,034	\$309,651	\$/yr
Urea (DEF) Savings	--	\$514	\$30,246	\$30,246	\$30,246	\$30,246	\$30,246	\$/yr
Maintenance Savings	--	\$19,592	\$7,486	\$48,740	\$54,210	\$63,634	\$63,634	\$/yr
TOTAL SAVINGS	--	\$33,525	\$109,078	\$181,189	\$335,217	\$470,914	\$403,531	\$/yr

Table 13
Operational Savings

FUEL AND RUNNING HOURS	(D) Diesel Mechanical (DM)	(A) Shaft Generator Vessel	(B) Diesel Electric (DE)	(C) DE w/Battery for Peak Share	(D) DE w/Battery & Shore Charge	(E) Battery Electric Vessel	(F) Fuel Cell Electric Vessel (Gray H2)	
Diesel fuel consumed	167,203	163,009	144,907	135,264	64,566	0	0	gallons/yr
LNG fuel consumed	0	0	0	0	0	0	0	gallons/yr
Electricity consumed	0	0	0	0	1,071,388	2,179,509	0	kWhe/yr
Hydrogen (gray) consumed	0	0	0	0	0	0	141,372	kg/yr
EMISSIONS TOTALS*								
Diesel Fuel CO ₂ emissions	1,702,122	1,659,433	1,475,150	1,376,987	657,285	0	0	kg CO ₂ /yr
LNG Fuel CO ₂ emissions	0	0	0	0	0	0	0	kg CO ₂ /yr
Electricity CO ₂ emissions	0	0	0	0	491,242	999,326	0	kg CO ₂ /yr
Hydrogen CO ₂ emissions	0	0	0	0	0	0	1,266,693	kg CO ₂ /yr
TOTAL EMISSIONS	1,702,122	1,659,433	1,475,150	1,376,987	1,148,526	999,326	1,266,693	kg CO ₂ /yr
*diesel emissions intensity per EPA; electric emissions intensity based on average for US								
TOTAL REDUCTION	--	42,689	226,972	325,136	553,596	702,797	435,430	kg CO ₂ /yr
1 Car = 4600 kg CO ₂ /yr - US EPA	--	9	49	70	120	152	94	cars off the road

Table 14
Emission Savings

4. Conclusion

Electrification has distinct advantages over traditional diesel mechanical powerplants for use in tug applications.

In all cases explored throughout this analysis the advantages are:

- 1- lower operational cost per year
 - a. Maintenance, fuel, urea, etc.
- 2- reduced engine running hours or elimination of engine hours in more advanced systems
- 3- lower CO2 emissions and thus a smaller yearly impact on the environment

The question of a hybrid or electric tug for an owner is very dynamic. Owners and operators are balancing the questions surrounding operational, commercial, and regulatory requirements for their vessel as technology has evolved and is evolving quickly in the tug segment.

A tug has a life expectancy of 30 years, but many market owners and operators can push the life expectancy for many more years. With the idea of a very long-life asset, owners and operators should closely consider electrification, and the benefits reviewed in this paper, for the future of their tug fleet.

Finally, this is not a one size fits all for every system and every tug. A thorough analysis such as the one explored throughout this paper should be undertaken to determine what system is right for your operation.



5. Additional Information

5.1. Listing of related documents

Ref #	Document Kind, Title
1	Optimizing fuel efficiency and emission reduction through intelligent power management for hybrid electric vessels; R. Chan
2	Implementation of Optimization-Based Power Management for All-Electric Hybrid Vessels
3	Step Aside, Green Hydrogen, There's a New, Cleaner Color in Town by Whitaker B. Irvin, Jr



ABB Inc.

3700 W am Houston Parkway S
Houston
TX 77042
UNITED STATES

[abb.com/marine](https://www.abb.com/marine)